

ULTRALUMINOUS INFRARED GALAXIES AND THE ORIGIN OF QSOS

D. B. Sanders^{1,2}

¹*Institute for Astronomy, Univ. of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822*

²*Max-Planck Institut für Extraterrestrische Physik, D-85740 Garching, Germany*

sanders@ifa.hawaii.edu

Abstract We review the evidence which suggests that ultraluminous infrared galaxies (ULIGs) are the precursors of optically selected quasi-stellar objects (QSOS) and discuss additional data that suggests that the majority, if not all QSOSs, may begin their lives in an intense infrared phase. Implications for the host galaxies of QSOSs are discussed.

1. INTRODUCTION

The discovery of a significant population of ultraluminous infrared galaxies (ULIGs) whose infrared luminosities, $L_{\text{ir}} \equiv L(8 - 1000\mu\text{m}) > 10^{12}L_{\odot}$, are equivalent to the bolometric luminosities of optically selected QSOSs, [i.e. $M_{\text{B}} < -22.12$, $(H_{\text{o}}, q_{\text{o}}) = (75, 0)$, equivalent to $M_{\text{B}} < -23.0$, (Schmidt & Green 1983)], was one of the major scientific results from the Infrared Astronomical Satellite (*IRAS*) all-sky survey (Soifer et al. 1987). Extensive ground-based follow-up studies of complete samples of the nearest ULIGs have clearly shown that strong interactions/mergers of molecular gas-rich spirals are responsible for triggering the intense infrared emission, which appears to be produced by a mixture of nuclear starburst and powerful AGN activity. It has been postulated that the AGN may dominate the L_{ir} output in the ULIG phase and that the majority of ULIGs may evolve into QSOSs (e.g. Sanders et al. 1988a).

Here we briefly summarise the most recent data for complete samples of nearby ULIGs in order to illustrate the major stages in the proposed evolutionary scenario from ULIG to QSO. New data on the properties of the host galaxies of ULIGs are presented and the consequences for the host galaxies of QSOSs are discussed.

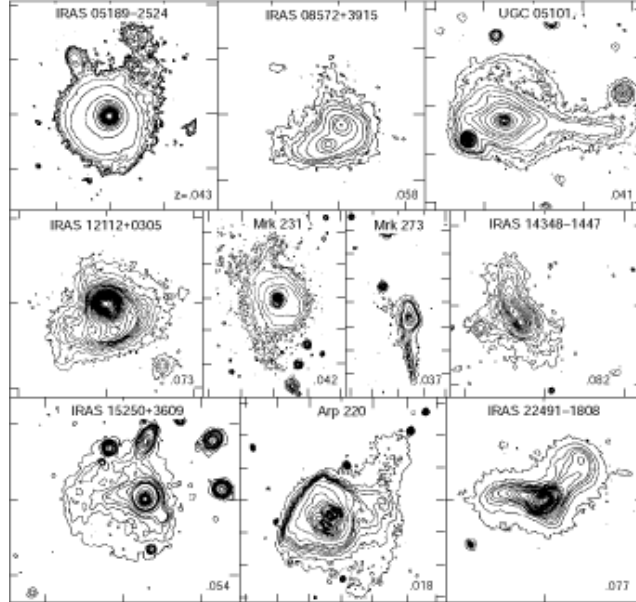


Figure 1. Optical (r-band) CCD images of the complete sample of 10 ULIGs from the original BGS (Sanders et al. 1988a). Tick marks are at $20''$ intervals.

2. AN EVOLUTIONARY SCENARIO: “COOL” ULIGS \rightarrow “WARM” ULIGS \rightarrow “IR-EXCESS” QSOS

What are the range of properties exhibited by ULIGs? Where did they come from and what are they evolving into? Extensive multiwavelength studies of the complete sample of objects in the IRAS BGS have provided the most detailed answers to these questions concerning the origin and evolution of ULIGs and their relationship to other classes of extragalactic objects. Sanders & Mirabel (1996) provide a comprehensive review of the available data on ULIGs, but for our purposes here Figures 1-5 will be sufficient to describe the general properties of ULIGs and to introduce our proposed evolutionary scenario.

The images shown in Figure 1 illustrate the range of morphology seen in ULIGs. Analysis of this sample of 10 ULIGs from the original IRAS BGS shows that all 10 are strongly interacting/merger pairs involving spiral disks of relatively equal mass ($<3:1$) near the endstage of the merger when the two disks substantially overlap and the two nuclei are close to or have already merged. Studies of larger samples of ULIGs have reported some variations on this theme, notably ULIGs with widely separated non-overlapping disks (e.g. Murphy et al. 2001) and ULIGs com-

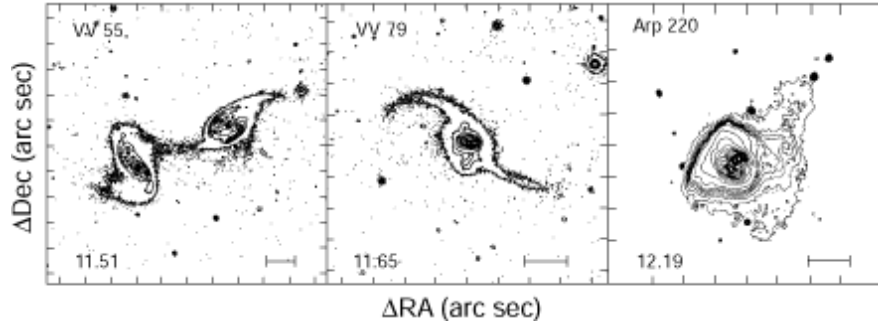


Figure 2. R-band images of LIGs (Mazzarella et al. 2001) from the IRAS BGS illustrating the strong interactions/mergers that are characteristic of nearly all objects with $L_{\text{ir}} > 10^{11.3} L_{\odot}$. The scale bar represents 10 kpc, tick marks are at $20''$ intervals, and the value of L_{ir} is indicated in the lower left corner of each panel.

posed of three or more interacting disks (e.g. Borne et al. 2000), both phenomena being observed in $\sim 15\text{-}20\%$ of the objects studied; however our own extensive study of a sample of 118 ULIGs suggests that such variations, if true, apply to a much smaller fraction ($< 3\text{-}5\%$) of the total population of ULIGs in the local universe (Veilleux, these proceedings).

Objects in the pre-ULIG phase can be seen in the images of the complete IRAS BGS. Most objects with $L_{\text{ir}} 10^{11.3} L_{\odot}$ appear to fall into a merger sequence which may result in a ULIG phase; L_{ir} generally increases with decreasing projected nuclear separation (see Figure 2). All of these merger systems involve disks which are both molecular gas rich. The fate of the molecular gas appears to be similar to what has been predicted from numerical simulations (e.g. Barnes & Hernquist 1991); enhanced star formation is observed as the gas disks collide, but eventually $\sim 40\text{-}70\%$ (depending on encounter geometry, relative velocity, etc.) of the total initial molecular gas mass is funnelled into a dense nuclear core (typically $R < 1\text{ kpc}$). Figure 3 gives a dramatic illustration of such an end product, with remnant star clusters still visible in the larger circumnuclear environs ($R < 5\text{ kpc}$) and a central dense gas core containing more than $10^9 M_{\odot}$ of H_2 gas. The bulk of the total L_{ir} in Mrk231 originates within the central $R < 0.5\text{ kpc}$ (Soifer et al. 2000). Whether a powerful nuclear starburst or accretion onto a massive black hole (MBH) dominates within the dense nuclear gas core is a subject of current debate (c.f. Joseph 1999; Sanders 1999), but it is clear that the conditions are favourable for both.

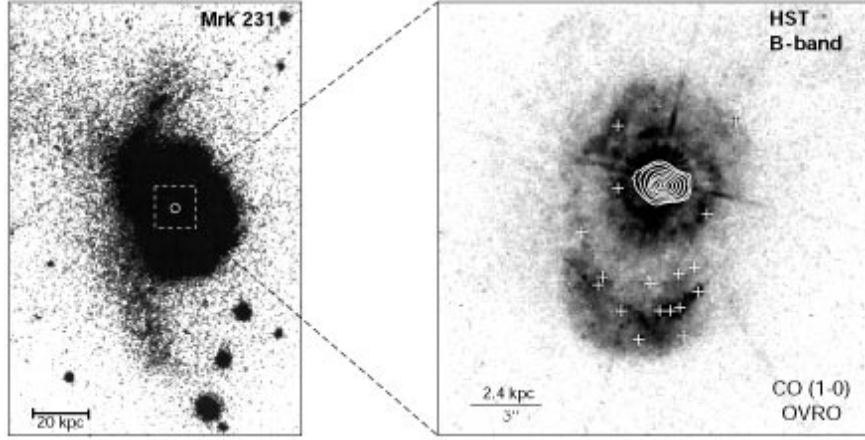


Figure 3. The “IR-QSO” Mrk 231. (left panel) - optical image and size of central molecular gas concentration (circle). (right panel) - HST B-band image and identified stellar clusters (‘+’) from Surace et al. (1998). The high resolution CO contours are from Bryant & Scoville (1996).

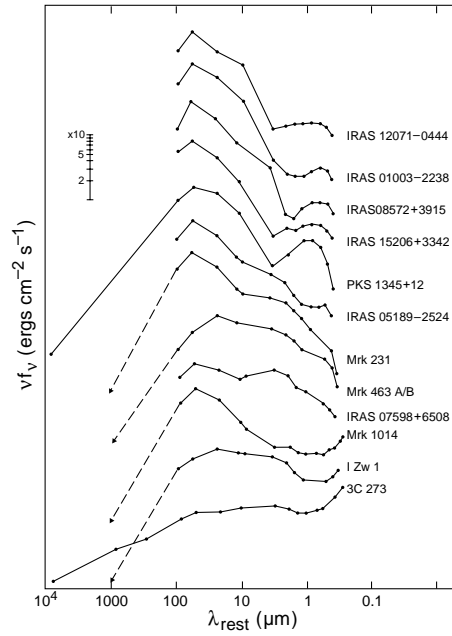


Figure 4. SEDs for the complete sample of 12 “warm” ULIGs from Sanders et al. (1988b). Sources are ordered (top to bottom) in order of increasing f_{25}/f_{60} ratio and increasing ratio of $L_{\text{opt-UV}}/L_{\text{IR}}$. Dashed lines are an extrapolation beyond the figure boundary to the data point at $\lambda = 6$ cm.

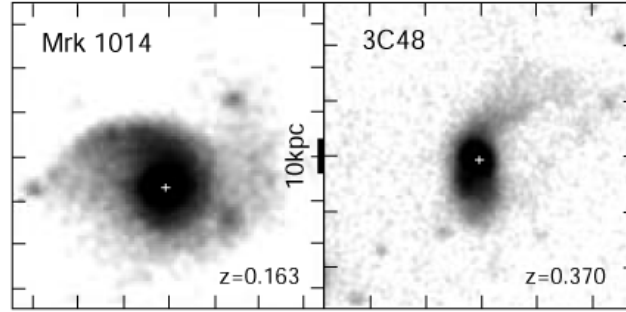


Figure 5. Optical images of “IR-excess”, optically selected QSOs (Mrk 1014 = PG0157+001 - MacKenty & Stockton 1984; 3C48 - Stockton & Ridgway 1991)

A significant subset of ULIGs, those exhibiting “warm” mid-infrared colors (i.e. $f_{25}/f_{60} > 0.2$)¹ give the strongest evidence favouring the hypothesis that the dominant luminosity source in the ULIG phase is an AGN. The three “warm” ULIGs in Figure 1 (IRAS05189-2524, IRAS08579+3925, Mrk231) all show broad Sy 1 emission lines in optical and/or near-infrared spectra (Veilleux et al. 1995), and the ratio of reddening-corrected $H\beta$ broad-line luminosity to L_{bol} is the same in these objects as is found for optically selected QSOs (Veilleux et al. 1999). In larger samples, the ratio of “cool” to “warm” ULIGs increases with increasing L_{ir} , from $\sim 15\%$ at $10^{12} L_{\odot}$ to $\sim 50\%$ at $> 10^{12.4} L_{\odot}$ (see Veilleux, these proceedings). The majority of the “warm” objects ($\sim 75\%$) exhibit a single merger nucleus as opposed to the “cool” objects where the mean nuclear separation is $\sim 2\text{kpc}$ and only $\sim 20\%$ of the sources exhibit a single nucleus (e.g. Kim 1995).

As in the small “warm” subsample of 3 ULIGs shown in Figure 1, larger samples of “warm” ULIGs show broad Sy 1 emission lines either in direct light or in polarised emission. And more importantly, a significant fraction ($\sim 10\text{--}15\%$) already exhibit the “big-blue-bump” characteristic of optically-selected QSOs. Figure 4 shows the complete radio-to-UV spectral energy distributions (SEDs) for a complete sample of 12 “warm” ULIGs (Sanders et al. 1988b) illustrating the progression from strong far-infrared excess through equally strong mid-infrared emission and finally to the emergence of a UV-excess phase. It seems reasonable to assume that the emergence of the “big-blue-bump” may be associated with the expulsion of gas and dust from the central regions through the

¹deGrijp et al. (1985) found that searches based on “warm” mid-infrared colors could be very useful for discovering new infrared-luminous Seyfert galaxies in the IRAS database

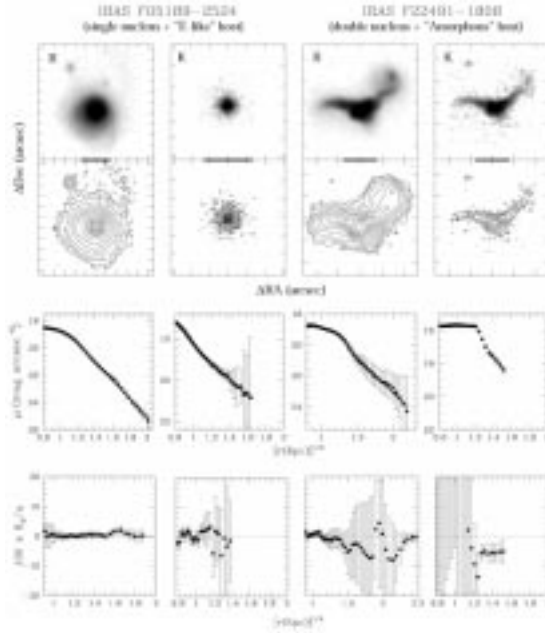


Figure 6. R-band and K-band images and 1-D surface intensity profiles for two ULIGs - the “IR-QSO” IRAS F05189–2524 and the “cool” ULIG IRAS 22491–1808 (Sanders et al. 2000)

combined action of radiation pressure and supernova explosions as indicated by the detection of nuclear superwinds (e.g. Armus et al. 1990) in many of these objects. Figure 5 shows images of two “warm” ULIGs which are also well-known QSOs (one RQQ and one RLQ). Both of these objects still show remnant tidal tails and both still contain relatively large amounts of molecular gas, consistent with the finding by Clements (2000) that those QSOs with the strongest far-infrared excesses are more likely to lie in visibly “disturbed” hosts.

3. THE HOST GALAXIES OF ULIGS: EVIDENCE FOR $S + S \rightarrow E$

High resolution optical and near-infrared images of the hosts of ULIGs from the IRAS BGS have shown that they appear to be evolving into elliptical galaxies with optical half-light radii and surface brightness values which lie on the fundamental plane defined by ellipticals (Kim 1995). Furthermore, the central gas surface densities of ULIGs are similar to the values found in disk galaxies, thus solving a long standing problem of how such dense cores could have formed (e.g. Kormendy & Sanders 1992). And Genzel et al. (2001) “confirm that ULIG merg-

ers are ellipticals-in-formation” based on near-infrared spectroscopy of 12 ULIGs from the IRAS BGS, which shows that these objects fall on or near the fundamental plane represented by intermediate mass ($\sim L^*$) disk ellipticals.

A more thorough analysis of the radial surface brightness distributions for all 118 ULIGs in the IRAS 1-Jy sample suggests that roughly 30% of the R-band radial surface brightness profiles are well fitted by an elliptical-like $R^{1/4}$ -law, with only 10% showing an exponential profile and 60% being “intermediate” (see Veilleux, these proceedings). Figure 6 gives examples of the observed radial profiles for a “warm” “E-like” ULIG and a “cool” “intermediate-type” ULIG. The “E-like” ULIGs still show evidence of dusty nuclei as evidenced by flat-topped R-band profiles and excess K-band light at $R < 1\text{--}2$ kpc, and the outermost radii are often affected by faint tidal debris. “Intermediate-type” ULIGs (the majority of all ULIGs) often show the effects of double nuclei at small radii ($R < 5$ kpc), a $R^{1/4}$ -law over much of the rest of the observable disk, but with strong asymmetries due to obvious tidal debris at large radii.

4. COMPARISON OF ULIG/QSO HOST MAGNITUDES AND COLORS

There is now sufficient high resolution imaging data on large samples of QSOs and ULIGs to permit a meaningful comparison of the basic properties of the hosts of both classes of objects, although caution is advised depending on which samples are selected. There is still a mismatch in redshift and bolometric luminosity distribution between the two classes of objects depending on which published samples are chosen. Problems with PSF subtraction in QSO images limits much of the analysis of QSO data to 1-D radial profiles and results in host magnitudes that suffer from somewhat uncertain extrapolations to small radii.

H-band imaging is thought to minimise the contamination from QSO nuclei so we present these results first. For QSOs, extensive H-band imaging of local (typically $z < 0.3$) “low- luminosity” QSOs shows that they typically lie in $\sim L^*$ host galaxies (McLeod & Rieke 1994a) while “high-luminosity” QSOs lie in $\sim 2L^*$ galaxies (McLeod & Rieke 1994b). H-band imaging of “cool” + “warm” ULIGs (typically at $z < 0.16$), which span a luminosity range sufficient to include all of the “low-luminosity” QSOs and approximately half of the “high-luminosity” QSOs, shows that ULIGs lie in hosts with total H-band luminosities in the range $\sim 0.5\text{--}5 L^*$ with a mean value of $\sim 1.5 L^*$ (Surace et al. 1998, 2000). Data at R-band and K-band for ULIGs and QSOs is also avail-

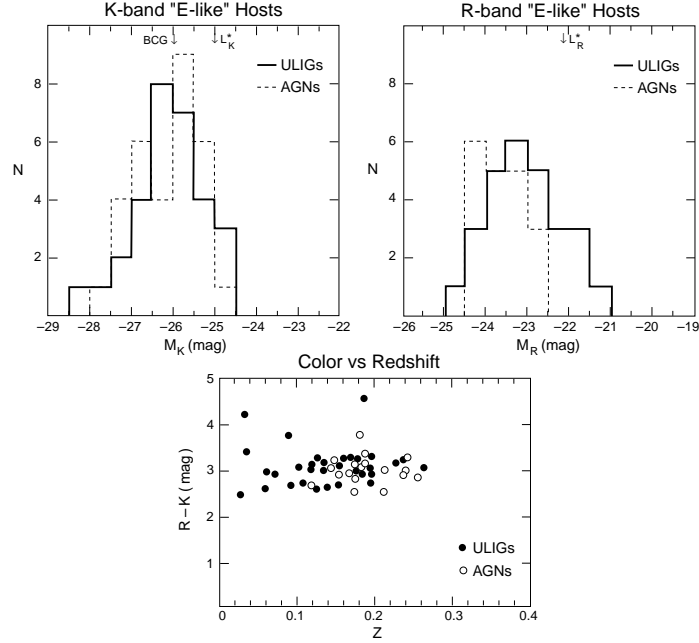


Figure 7. R-band, K-band, and (R–K) colors for the hosts of those ULIGs with single nuclei and $r^{1/4}$ -like radial profiles (i.e. “E-like”: see Kim 1995), compared with recently published K-band and R-band data for the hosts of AGNs (Taylor et al. 1996; McLure et al. 1999).

able, but in the case of ULIGs much of it is not fully reduced. However, Figure 7 gives a preliminary comparison of data for a subsample of ULIGs with “E-like” profiles with QSOs showing that both samples have similar R-band and K-band magnitude distributions and similar R-K colors.

Finally, the radial profiles of QSO hosts have now been published by several groups (e.g. Hutchings 1987; Véron-Cetty & Woltjer 1990; McLeod & Rieke 1994a,b; Taylor et al. 1996; McLure et al. 1999; McLeod & McLeod 2001; Percival et al. 2001), with some of the more recent surveys appearing to solidify many of the claims made in the earlier analyses. RLQs appear to lie in “E-like” hosts (as do radio galaxies of similar radio luminosity). A significant fraction of RQQs have spiral-like hosts, but Dunlop (these proceedings) discusses the possibility that this is simply a luminosity effect, and that above $\sim 3\text{--}4 L^*$ both RQQs and RLQs are found almost exclusively in “E-like” hosts. However, examination of all of the existing imaging data for QSOs shows that a significant fraction of all QSOs have radial profiles that are often somewhat ambiguous, and that even “E-like” profiles often exclude obvious tidal debris

at large radii as well as observable 2-D structure (e.g. embedded disks and/or bars) at small radii (e.g. Surace, these proceedings).

Comparing the 1-D radial profiles of QSOs and ULIGs, it is clear that a smaller fraction of ULIG hosts are described as “E-like”. However, given that the majority of ULIGs are radio-quiet and that the ULIGs studied so far are heavily biased toward the lower luminosity range of the above QSO surveys, the results for the two samples may not be all that different.

5. NEW DATA ON THE HOSTS OF QSOS

Here I simply call attention to several important new results, including those reported at this workshop by our group and others, concerning the infrared and molecular gas properties and evidence for star formation in the host galaxies of QSOs. Evans et al. (2001) and Evans (these proceedings) have shown that infrared-excess, optically selected QSOs appear to contain substantial amounts of molecular gas, $M(\text{H}_2) \sim 10^8 - 10^{9.5} M_\odot$, similar to the distribution of H_2 gas content found for “warm” ULIGs. Surace et al. (2001) and Surace (these proceedings) have shown that infrared-excess QSOs exhibit “knots” of star formation, and considerable 2D structure in the form of tidal debris and/or inner bars or disks. Canalizo & Stockton (2001) also report that all “transition” QSOs (objects which overlap with our samples of “warm” ULIGs and infrared-excess QSOs) show evidence for strong recent star-forming activity and that this activity can be directly related to a tidal interaction. In addition, Haas et al. (2000) and Haas (these proceedings) confirm the existence of “considerable dust emission” from a sample PGQSOs that span a wide range of luminosity, and report that the SEDs of nearly all PGQSOs studied resemble those of “warm” ULIGs.

6. SUMMARY AND FUTURE WORK

The current data for ULIGs in the local universe provides strong evidence that the hosts of ULIGs are created by the merger of gas-rich spirals and that the merger product already is or shortly will be a disky elliptical. Most of the infrared activity in ULIGs is confined to the inner few kpc with the larger disk experiencing a decaying starburst. The debate continues over the dominant nuclear luminosity source responsible for the intense infrared emission in the “cool” ULIGs with some consensus having been reached that it is an AGN for the “warm” ULIGs. In turn, recent data on lower luminosity RQQs is consistent with their having evolved from a “warm” ULIG phase. However, support for the full evolutionary scenario (“cool” ULIG \rightarrow “warm” ULIG \rightarrow “IR-

excess” QSO→QSO at all ULIG/QSO luminosities and all redshifts remains elusive.

An alternative view of the ULIG→QSO evolutionary scenario is that it simply does not exist, and that the two populations have essentially different origins and fates. Intriguing evidence presented by Dunlop and collaborators (Dunlop, these proceedings) suggests that the hosts of QSOs are old ellipticals (e.g. Nolan et al. 2001) where the spheroid (and presumably the MBH) was put in place long before the current observed QSO phase (as opposed to a precursor ULIG phase). The suggestion is then raised that a minor interaction (or other such fuelling event) has simply recently re-energised the black hole. Further observations, perhaps coupled with better modelling of the merger process that can provide more accurate age dating of the merger remnant, are clearly needed to resolve these competing views.

Acknowledgments

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